



RESEARCH DEPARTMENT



REPORT

Loudspeaker distortion associated with low-frequency signals

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LOUDSPEAKER DISTORTION ASSOCIATED WITH LOW-FREQUENCY SIGNALS

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H.D. Harwood, B.Sc.

(PH-90)

A handwritten signature in black ink, appearing to read 'P. Lange', with a stylized, cursive script.

Head of Research Department

LOUDSPEAKER DISTORTION ASSOCIATED WITH LOW-FREQUENCY SIGNALS

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LOUDSPEAKER DISTORTION ASSOCIATED WITH LOW-FREQUENCY SIGNALS

Summary

Three differing forms of distortion, which are associated with low-frequency signals in loudspeakers, are investigated.

It is shown that distortion due to the Doppler effect can be compared with that due to wow and flutter in recording machines and subjective data obtained for this purpose can be applied to loudspeakers. Generalised design limits for loudspeakers are calculated and it is seen that present BBC designs lie within these limits.

In loudspeakers designed to reproduce low frequencies, the voice coil is made longer than the magnetic field. At low frequencies, when the amplitude of vibration of the cone exceeds the difference in length, it is shown that instead of the peaks of the waveform being clipped, expansion of the input/output curve takes place. This effect, with its associated distortion, can be compensated by employing an appropriate non-linear suspension and thus a much greater useful output can be obtained than by using a linear suspension.

Finally, a vented cabinet is often used to reduce the magnitude of the undesirable effects previously mentioned as well as to extend the bass response. However, a vented cabinet is a resonant system and high sound pressures and particle velocities are produced in the vent. These are liable to give rise to distortion from the inherent non-linearity in the air and from turbulence at the orifice and in the pipe. Existing data are used to estimate the sound levels which may be generated in a typical listening room before distortions from any of these causes is audible. It is also shown that this form of distortion is not a troublesome factor in the design of the BBC studio monitoring loudspeaker.

1. Introduction

1.1. General

It is generally desirable for a loudspeaker to have a uniform axial response/frequency characteristic and under these conditions the loudspeaker unit must be mass controlled; that is, it must operate above the fundamental resonance frequency due to the mass of the cone and the stiffness of the unit plus that of the air in the cabinet. It follows that both the amplitude of vibration (peak cone displacement 'A') and the cone velocity 'V' are greatest at low frequencies ($A \propto 1/f^2$, $V \propto 1/f$) and may increase further around the frequency of resonance; various forms of distortion which are dependent on these two factors will therefore be greatest at the bass end of the spectrum. This report deals with three forms of distortion which are most prominent in this region.

1.2. Doppler distortion

One such form of distortion is due to the large cone velocities in the bass, giving rise to the Doppler effect.

When a sound source and an observer move relative to one another, there is a change in the pitch of the sound and this phenomenon is known as the Doppler effect. This change in pitch is often observed when two cars pass each other and the frequency at the point of observation is given by the formula

$$f_o = \frac{v - v_o}{v - v_s} \cdot f_s$$

where v is the velocity of sound in the medium, v_o is the velocity of the observer in any direction, v_s is the velocity of the source in the same direction, and f_s is the frequency of the source.

In loudspeakers this condition may arise, for example, if both a low and a high frequency sound are being radiated from the same cone; the source of high frequency can be regarded as moving backwards and forwards at the low frequency rate and this will give rise to frequency modulation with its associated side bands, an effect known as Doppler distortion. For low values of modulation, the frequencies and amplitudes of these sidebands are the same

as those of some of the intermodulation products which would be generated by amplitude non-linearity; the only difference is the phase relationship. It is therefore very difficult to measure separately these two effects.

As in many aspects in the high fidelity reproduction of programme, much has been written on the subject, some authors claiming that Doppler distortion is the cause of all evils¹ and describing it as 'The Mud Factor' whilst others claim that the effects are negligible.² No substantial evidence as to the validity of either statement has been produced.

In this regard the subject can be approached from another angle for which subjective data is available. This report gives quantitative information on the behaviour of certain recent high-quality loudspeaker designs and also generalised data to determine the minimum sound level in an average-sized listening room before Doppler distortion is observed from various sizes of loudspeaker cone.

1.3. Non linearity distortion due to finite length of magnetic field and voice coil

A second form of distortion which is most serious at the low end of the frequency range is due to the large amplitude of the cone. In a loudspeaker unit designed to reproduce this end of the spectrum, the length of voice coil is a compromise between that required for maximum sensitivity and that for maximum power output. The voice coil is always longer than the magnetic field and the amplitude will be a linear function of input, from this point of view, until it is equal to the difference in the two lengths. For amplitudes greater than this in conventional loudspeaker units, non-linearity distortion sets in but it will be shown that this can be avoided or at any rate reduced to negligible proportions until the amplitude is considerably greater than the difference in the two lengths.

1.4. Non linearity distortion in vents

A common method of reducing the distortions associated with excessive cone velocity and amplitude, is to use a vented cabinet, which also has the advantage of increasing the range of the low-frequency response. In this type of design, the acoustic compliance of the air in the cabinet resonates with the inertance of a vent at a specified low frequency as a Helmholtz resonator, and the device acts as an acoustic impedance transformer presenting a high impedance to the rear of the loudspeaker cone and a low impedance to the air. Now a vent may be divided into two extreme classes. It may consist of a simple orifice, that is a hole whose length is small compared with its diameter, or it may consist of a pipe whose length is large compared with its diameter. The acoustic radiation resistance of the vent is independent of its area³ and the vent area is therefore often made much smaller than that of the cone as this avoids, or reduces, the need for a pipe in series with the orifice to obtain a given inertance. It follows, however, that the sound particle velocity in the vent for a given overall sound pressure must be high. The vent is not streamlined and therefore turbulence will be generated; it is clear that this will be greatest when the vent is short, and there-

fore have a small area for a given inertance, so that the velocity is correspondingly high. Some guidance is therefore desirable as to how small the orifice may be before appreciable non-linearity distortion is generated. If, however, a pipe is connected in series with the vent in order to increase the area for a given inertance then distortion due to the finite sound pressure or turbulence may take place in the pipe, and these represent other design limits. This report examines these limits to see how present high-quality loudspeaker designs lie with regard to them and to obtain generalised design data, applicable to any loudspeaker, for this form of distortion.

2. Doppler distortion

2.1. General

In 1943 Beers and Belar⁴ gave a formula for the ratio of the power in the sidebands to the total power in the sound wave in per cent at:

$$D = \frac{2900f_2\sqrt{p_1}}{f_1^2 d^2}$$

where f_1 is the modulating frequency in hertz

f_2 is the modulated frequency in hertz

p_1 is the acoustical power at f_1 in watts

and d is the effective piston diameter in inches.

This formula has been used ever since, often in an erroneous manner.

It should be noted that the percentage distortion rises directly as the modulated frequency f_2 and as the square root of the power at f_1 , and that the formula will give the same degree of distortion if the former is doubled as if the latter is quadrupled. Unfortunately it has been widely assumed that the factor D gives a unique *subjective* assessment of the distortion, a claim which the authors never made. This would assume, for example, that if the modulated frequency were increased from 20 kHz to 40 kHz, i.e. in the inaudible ultrasonic band, the increase in distortion would be equal to that for a 10 kHz band but with a corresponding increase in power level, a result which is clearly wrong. Such an idea also makes certain assumptions concerning f_1 , i.e. that the distortion will sound uniformly worse as the frequency is lowered and as we shall show later, this is not the case.

Further it has been widely assumed that the audibility of the percentage distortion arrived at by using this formula should bear a close relationship to that obtained for distortion due to non-linearity so that anything in excess of one or two percent has been regarded with dismay (figures for Doppler distortion up to 57% have been quoted). In contrast to this, to the present author's knowledge, no subjective evaluation of Doppler distortion as such has ever been carried out. We must therefore try and assess what these figures, which on paper look so alarming, really involve, and it will be shown that on the basis of other tests, quite a large percentage of Doppler distortion may be, in fact, inaudible.

The frequency modulation of high frequencies by a low frequency in a loudspeaker can be regarded as a form of flutter distortion similar to that experienced in tape, disc or film recording systems. As in these systems, all frequencies are subjected to a modulation which depends directly on the ratio of the velocity of the loudspeaker cone to that of sound in air. Now figures already exist⁵ for the percentage values of flutter of various frequencies which are just audible using the most sensitive type of programme (excluding pure tone) and it would therefore appear to be profitable to apply these criteria to some monitoring loudspeakers to see where they stand in this regard. This principle which will be followed will be to determine the peak velocity of the loudspeaker cone at the maximum rated sound level and calculate what percentage flutter this will produce assuming that the energy is concentrated almost entirely at the worst, i.e. lowest, frequency. In the case of a vented cabinet, the velocity of the cone is considerably reduced in the region of vent resonance and a correction will have to be applied for this.

2.2. Application

The loudspeakers which will be examined represent typical recent designs. One has a 30 cm low frequency unit, whilst the others have 20 cm and 13 cm low frequency units respectively.

2.2.1. Loudspeaker with 20 cm low-frequency unit

This loudspeaker will be examined first as it is likely to be the most seriously affected by this form of distortion and illustrates well the principles involved; it employs a 20 cm low frequency unit and a 5.5 cm high frequency unit. The maximum sound level for this loudspeaker is rated at 100 dB wrt 2×10^{-5} N/m² in an average listening room with a reverberation time of 0.4 sec.

From Olson⁶ it is seen that the acoustical sound power required to generate this sound level in a room of 2000 ft³ (60 m³) is 0.3 watts.

The loudspeaker has a uniform axial response/frequency characteristic down to 50 Hz, below which it falls off rapidly, but the cone output is modified by the vented cabinet having a vent resonance of 40 Hz. Measurements of separate cone and vent outputs show that allowing for this factor the output from the cone alone is down by 3 dB at 50 Hz.

Now the author has shown elsewhere⁷ that for a given overall sound level the spectrum is such that the peak level of programme at 50 Hz is 8 dB down on the maximum overall figure, this data is reproduced in Fig. 1.* Due to the two factors the actual maximum power output at 50 Hz from the cone of this loudspeaker is 25 milliwatts for an overall programme sound level of 100 dB.

* The peak shown at 70 Hz was shown to be due to only one note, from a bass guitar, out of all the programme examined, and was therefore felt to be atypical. The smoothed curve was accordingly drawn below it.

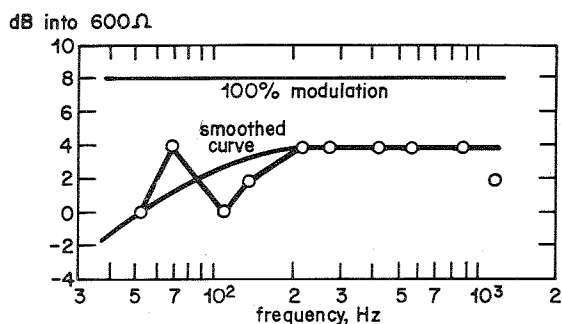


Fig. 1 - Peak octave analysis of Programmes, all items

In this loudspeaker the effective piston diameter of the 20 cm low frequency unit is 16 cm. The peak cone velocity corresponding to this power at 50 Hz is 117 cm/sec and therefore the ratio of the peak velocity to that of sound in air is 0.35%. This corresponds with the percentage flutter in recording machines.

Axon and Stott show⁵ in Fig. 10 of their paper and reproduced here as Fig. 2 that the minimum detectable level of flutter on piano music is not constant but varies with the frequency of flutter. It is about 1% at 50 Hz for the average observer and 0.85% for the most sensitive group. It will be seen that the flutter produced by this loudspeaker should be quite inaudible even to the most sensitive group by a factor of about 7 dB.

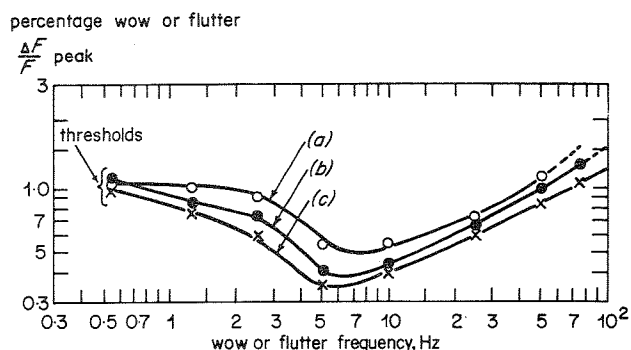


Fig. 2 - Variation of subjective threshold for sinusoidal frequency modulation of piano programme heard through loudspeaker:

- (a) mean for 16 nontechnical subjects
- (b) mean for all subjects (70)
- (c) mean for 14 female subjects

Several points should be noted here in this condition.

- (a) The conditions assumed for the loudspeaker are the most stringent conceivable as regards level and spectrum.
- (b) The type of programme chosen by Axon and Stott, for their tests, was the most critical they could find for sensitivity to flutter.
- (c) Axon and Stott's figures are for the whole frequency range. In the case of the loudspeaker under consideration, the crossover frequency from the low frequency unit to the high frequency unit is 3 kHz. Whilst it is not accepted that Beers and Belar's expression for Doppler distortion gives a correct subjective evaluation of the effect of bandwidth, this

bandwidth restriction can only affect the threshold of audibility in the direction of raising it. The loudspeakers are therefore clear of the subjective threshold by an even greater figure than that shown above, and there is a considerable margin of safety in the design.

(d) The percentage Doppler distortion for this loudspeaker unit is no less than 16%. If the low-frequency unit covered the full frequency range, say up to 15 kHz, the distortion figure would actually be 80%. Yet the subjective results given by Axon and Stott do cover the full frequency range so even the distortion given by this enormous figure should still be inaudible! It is clear therefore that the figures for Doppler distortion should in no way be compared with those due to non-linearity distortion.

(e) The figures quoted from Axon and Stott apply to programme only. It is well known qualitatively, and shown in the paper by the above authors quantitatively, that the sensitivity of the ear to flutter is much more acute for steady pure tones.

2.2.2. Comparison of Doppler distortion from differing designs of loudspeaker

The Doppler distortion from the other loudspeakers can be similarly calculated. The results together with the essential design information are given in the table below.

TABLE 1

Comparison of Flutter from Various Loudspeakers

Nominal diameter of units	20 cm and 5.5 cm	30 cm, 20 cm and 5.5 cm	13 cm and 11 cm
Effective diameter of units	16 cm and 3.5 cm	25 cm, 16 cm and 3.5 cm	10 cm and 2 cm
Crossover frequencies	3 kHz	400 Hz and 3 kHz	3 kHz
Type of cabinet	Vented	Vented	Closed
Rated sound level dB wrt 2×10^{-5} N/m ² in room of 60 m ³	100	103	95
Low frequency cut-off Hz	50	50	75
% flutter	0.35	0.2	0.35
Minimum audible flutter at cut-off frequency (Most sensitive group from Fig. 2)	0.85	0.85	1.1
Minimum safety factor (dB) (objective)	7	12	10

A point which should be emphasised is that since the crossover from the low frequency unit in the second loudspeaker to the middle frequency unit is only 400 Hz, the subjective effect of the Doppler distortion is likely to be even less than that shown objectively when compared with the other two types of loudspeaker.

The examples given cover a wide range of units and indicate that, for most purposes at least, the limitation of

sound level is set by power handling capacity, i.e. heating of the voice coil, rather than by Doppler distortion.

2.3. Design criteria

Using the values of programme spectrum from Fig. 1 and the liminal values for flutter distortion from Fig. 2 we can now calculate the minimum sound levels permissible in a room of 2000 ft³ (60 m³) for various sizes of radiator before Doppler distortion is audible on the most critical type of programme. In arriving at these figures it is also assumed that the loudspeaker is of the *closed-cabinet* type and that the axial response/frequency characteristic is uniform down to the frequency given i.e. either 40 Hz or 100 Hz; if a vented cabinet is employed allowance must be made for the damping effect of the vent resonance on the cone velocity. In addition, it should be appreciated that the diameter given is that of the actual radiating surface not that of the loudspeaker chassis.

Under these conditions the criteria for loudspeakers having a lower cut-off frequency of 40 or 100 Hz are given in Fig. 3.

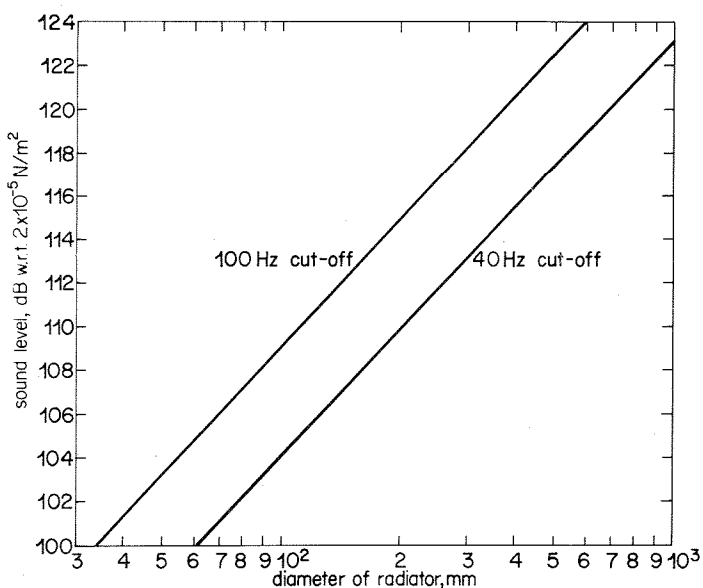


Fig. 3 - Minimum programme sound level in room of 2000 ft³ (60 m³) before Doppler distortion is audible, for radiators of various diameters and cut-off frequencies

As a final point it should be noted that the figures given apply just to the low frequency unit of a multi unit loudspeaker as in a good design the only danger of trouble from the Doppler effect arises in this unit. From this aspect the practice common in 'hi-fi' circles of employing only a capacitor in series with an m.f. or h.f. unit in order to act as a high-pass filter is to be deprecated. Under these conditions and for a constant voltage input to the capacitor, the unit operates at constant velocity, i.e. independent of frequency, below the crossover frequency down the vicinity of the bass resonance, instead of the velocity being reduced, as is desirable. As the unit is now being fed from a high impedance electrical source, there is very little electro-dynamical damping at resonance and if the mechanical Q is

high, as it usually is, the maximum velocity reached by the unit with this rudimentary form of crossover network may be enough to cause trouble from Doppler distortion. The cure is obvious; the crossover network should have an attenuation characteristic of at least 12 dB/octave below the crossover frequency and the damping applied to the unit, either mechanical or electromechanical, should be considerable.

3. Non-linearity distortion due to finite difference in length of magnetic field and voice coil

3.1. General

In the midband region, and at higher frequencies, the impedance of a loudspeaker unit consists essentially of the d.c. resistance of the voice coil in series with its inductance and the current flowing through the coil is therefore independent of the coil amplitude. So if a sinewave signal is applied to the loudspeaker at say 500 Hz, and the input is increased until the amplitude of the cone is sufficiently great that the voice coil no longer vibrates entirely in the magnetic field, the driving force at the peaks of the signal will fall off and symmetrical clipping of the peaks of the waveform will take place. This result does not apply, however, at low frequencies.

In the bass, and particularly around the resonance frequency, the mechanical impedance of the cone system is low and therefore the portion of the electrical impedance due to the motion of the voice coil in the magnetic field, known as the motional impedance, is correspondingly high; in a typical case it may reach ten times the resistance of the voice coil. The motional impedance is proportional to $(\text{flux})^2$ with the result that if the flux in a loudspeaker unit is doubled, the amplitude for a given low frequency input voltage is halved, not doubled as might appear at first sight. This is because the impedance is multiplied by four, and the current is therefore reduced to one quarter; one quarter the current in a field of twice the flux gives one half the driving force. Now in the converse situation, which is equally true, where the amplitude of the voice coil is large enough for the coil to be partially outside part of the magnetic field, the average flux cutting the voice coil is less and the amplitude for a given voltage is therefore increased. The output waveform for a sinewave input is therefore peaked instead of clipped, but the fundamental component is also increased until an amplitude is reached where the average flux and therefore the motional impedance, is so reduced that it is no longer the determining factor. Above this level of input the output will become limited and the input-output curve will resemble that given in Fig. 4.

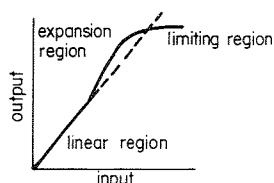


Fig. 4 - Schematic input/output relationship for loudspeaker unit

Now it may not be clear that, apart from knowing the truth, the position is any better off, as it is evident that distortion will be produced in the non-linear region whether the waveform is clipped or peaked, but in fact this information can be put to good use.

Neither the stiffness due to the spider/surround combination nor that due to the enclosed air in the cabinet is inherently linear. In practice the stiffness of the former follows a cubic law whilst the latter follows a quadratic law. As however, in practice, the distortion due to the latter is less in quantity and also less objectionable, there has been a trend in design towards making the mechanical stiffness smaller in order to allow the air stiffness to predominate. This must not be taken too far however or, due to gravity, the position of the voice coil in the air gap will vary with the angle of inclination of the loudspeaker. Later designs have therefore included some extreme measures,⁸ to make the mechanical stiffness more linear too, although it should be noted that improved linearity of the suspension cannot improve the non-linearity of the driving force. Another approach has been made⁹ purporting to linearise the amplitude by using a graded winding to the voice coil, the inner turns being well spaced apart, whilst the outer ones are contiguous. This would not only reduce the sensitivity but would also introduce a driving force which increased with amplitude and, of course, far from improving this already non-linear factor would make it worse; it is in any case rather impractical. The approach proposed here is different.

The spider in particular is in essence a flat diaphragm and the stiffness is non-linear for any but the smallest amplitudes, becoming stiffer as the excursion is increased. To reduce this non-linearity, corrugations are normally impressed into the diaphragm and in this way the degree of non-linearity can be controlled. If a spider/surround system is employed which increases in stiffness at the correct rate, exact compensation for the increase in driving force with amplitude is possible thus linearising the whole system, and extending the maximum power output, for a given degree of distortion, without affecting the sensitivity.

3.2. Application

The 20 cm bass unit, used in one of the loudspeakers discussed in the previous section can be taken as an example. In this case the length of the voice coil is 0.63 cm, and the nominal length of the pole pieces is 0.53 cm giving a possible amplitude of 0.1 cm before non-linearity occurs. The length of the magnetic field does tend to exceed that of the pole pieces by about 0.05 cm owing to the lines of force bending at the ends of the pole pieces, but it will be assumed as a first approximation, that in fact the field plot is 'rectangular' i.e. is constant up to the ends of the pole pieces and then falls abruptly to zero. Under these conditions, assuming the customary constant voltage source, it is possible to compute* the amplitude of the cone for varying sinewave inputs and also the corresponding level of distortion, which, owing to the inherent symmetry of the

* Calculations done by J.W. Head, see Appendix.

system, is largely third harmonic. (Because of the simplifying assumption of a rectangular magnetic field plot it is probably not profitable to compute higher orders.) The results are given in Fig. 5.

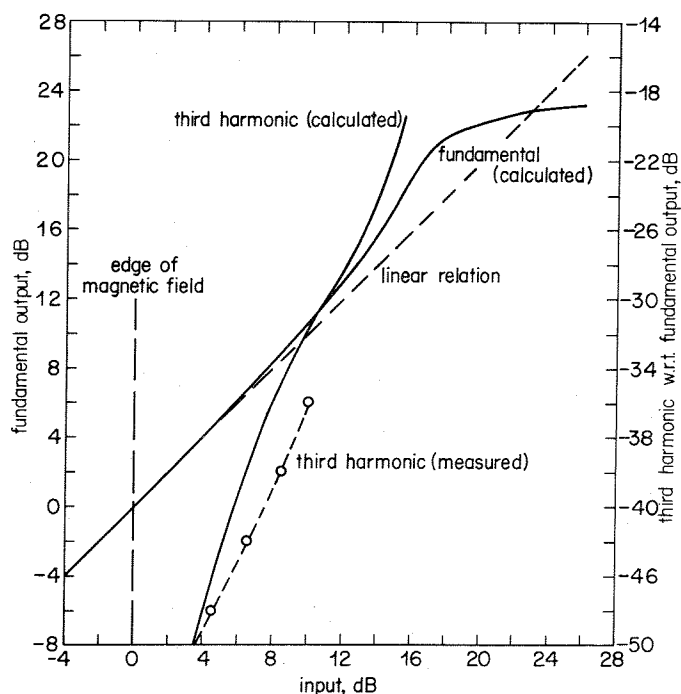


Fig. 5 - Relation between calculated levels of fundamental and third harmonic for a linear stiffness, and measured third harmonic for a non-linear stiffness, for various input levels to loudspeaker

The general form of the curve for the fundamental is as expected, and it would appear both possible and highly profitable to compensate for the rise in fundamental output up to an input of 16 dB. Note that for this level of input the third harmonic distortion alone for a perfectly linear suspension system is -14 dB with respect to the fundamental, i.e. 13%, a level which would be intolerable subjectively.

These calculated curves were not checked by measurement as it would have required substantial effort to produce the necessary linear suspensions. Instead the converse was done, that is an available suspension known to be non-linear was used to see how much improvement it would produce in practice. The law of deflection versus applied force was measured d.c. wise by the application of known masses to the cone and measuring the displacement. The results are shown in Fig. 6 plotted on a logarithmic scale to make comparison with Fig. 5 simple. The peak cone amplitude for a given level of a low frequency signal was then measured when the unit was mounted in a closed cabinet and the corresponding third harmonic distortion determined in a free field room. The results are also plotted in Fig. 5 and it will be observed from this curve that for a given level of distortion an increased level of 2 dB i.e. 60% in power, can be produced by the loudspeaker with the non-linear suspension. There seems to be no obvious reason to doubt that with the correct degree of non-linearity in the com-

bination of suspension and air stiffness, the third harmonic distortion could be reduced even further, although it is almost certain that even now the degree of distortion shown for an input level of +10 dB, i.e. 1.6% is inaudible. (Greater inputs were not feasible as the spider hit the pole pieces above this level.)

Now it may be argued that the assumption of a rectangular field plot is inaccurate and that the fringing of the field which must necessarily take place at the end of the magnetic structure will affect the result. This is correct but note the direction in which it does so. If the field in effect extends at each end 0.025 cm beyond the steel poles the difference in length between field and voice coil is reduced to 0.05 cm and therefore our theoretical curve in Fig. 5 should be displaced 6 dB to the left. This has the effect of increasing the improvement in power output with the non-linear suspension from 2 dB to 8 dB for the same degree of distortion.

Finally it should be mentioned that this non-linear suspension is already used in one of the 20 cm loudspeaker units described in the previous section and it was the observation that the undistorted output exceeded the theoretical value which was the starting point of this investigation.

4. Non-linearity distortion in the vent of vented loudspeaker cabinets

4.1. General

The two main recent investigations of acoustic non-linearity of orifices are by Bies and Wilson¹⁰ and Ingard and Ising.¹¹ In both experiments Helmholtz resonators were employed in order to obtain high particle velocities, without the use of a source of excessively high sound pressures

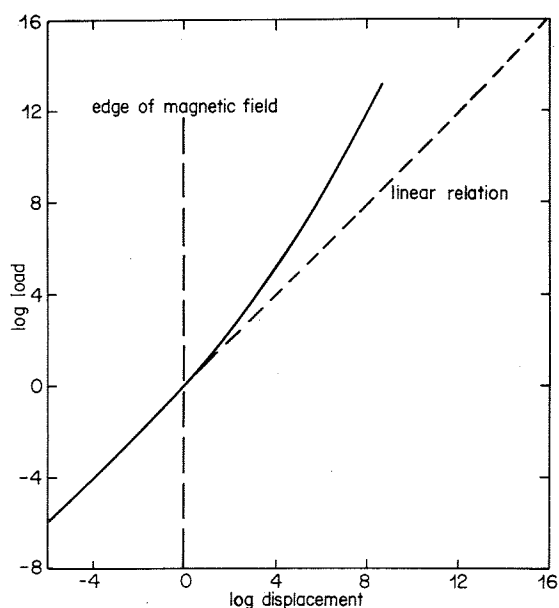


Fig. 6 - Relationship between load and displacement for 20 cm loudspeaker unit

in the latter case, and in both cases to enable short orifices to be examined. In the former experiment the orifice was 2.85 cm long and 9 cm in diameter and is therefore representative of actual vents used in loudspeakers; in the second case the orifice was made much shorter to emphasise the end effects and was only 0.1 mm long and 6 mm in diameter, thus representing an extreme case. Note however that in both cases the diameter is much larger than the thickness.

Bies and Wilson show in their Fig. 1 that the acoustic resistance of the orifice is constant for particle velocities up to about 60 cm/sec. gradually rising in value above this velocity as turbulence sets in. Ingard and Ising show (in their Fig. 21) good agreement with this conclusion although they indicate that the resistance may not be perfectly constant even for lower velocities. On the other hand waveform traces are given in their Fig. 2, which show no visible harmonic distortion even for velocities* of 2.7 m/sec.

As a compromise between these two values it is worth examining a round figure for maximum velocity of 1 m/sec. Note that the figure for the critical velocity is independent both of the size of the orifice and of frequency. However, the total percentage distortion obtained for a given sound pressure depends on the size of the orifice and there is therefore from this point of view, an advantage to be obtained in using a fairly large orifice in loudspeaker design.

Against this conclusion is the fact that a large orifice will need a pipe in series with it to enable a given value of inertance to be obtained and when high sound pressures are propagated along a pipe distortion is generated, in the first place mainly of the second harmonic type.

Thuras et al¹² give the second harmonic distortion in a planewave, e.g. in a pipe as

$$P_2 = \frac{(\gamma + 1) w p_1^2 x}{20\sqrt{2}\gamma p_0 c}$$

where p_1 is the fundamental pressure in N/m^2

γ is the ratio of specified heats

w is $2\pi f$

f is frequency in hertz

c is velocity of sound in cm/sec

x is distance in cm

and p_0 is the static pressure in N/m^2

The levels of the third and higher harmonics are appreciably lower than that of the second harmonic. It is seen that for a given sound pressure in the pipe the distortion is independent of the diameter of the pipe but proportional to its length and to frequency. Increasing the diameter of the pipe would, for the same inertance, require

a greater length; however, the sound pressure in the pipe would be less and the resulting distortion would be lower. Fortunately, in the present case, the distortion is least at the low frequencies at which a vent is used.

Finally, high sound pressures in the pipe also involve high velocities and turbulence will occur in the pipe above a critical velocity, the value of which is a function of diameter. Reynolds showed that for steady flow the ratio

$$\frac{v_c d}{\eta} \text{ is a constant}$$

where v_c is the velocity in cm

d is the diameter in cm

and η is the cgs kinematic viscosity, i.e. the dynamic viscosity divided by the density.

In fact the constant, called Reynolds number, is not really fixed but for the present circumstances is about 2300.

Note that in this case the critical velocity is inversely proportional to the diameter of the pipe with a corresponding effect on sound powers available.

4.2. Application

4.2.1. Distortion due to an orifice

From the information provided in the previous section it is possible to calculate the sound levels produced by orifices of various diameters when the sound velocity is the maximum specified and for vent resonance frequencies in the range of 30 to 100 Hz, values commonly used.

Olson¹³ gives the peak amplitude of a 10 cm diameter piston mounted in an infinite baffle and radiating a sound power of 1 watt as 11.4 cm at 40 Hz, this being equivalent to an rms velocity of 10 m/s. The far field sound level in a listening room of 2000 ft³ (60 m³) for an omnidirectional source for this sound power¹⁴ will be 102 dB wrt $2 \times 10^{-5} N/m^2$, or for a velocity of 1 m/s a figure of 82 dB will be obtained. Now it was shown earlier in Fig. 1 that the programme spectrum is such that the power in an octave band at 40 Hz is about 10 dB below the peak signal level, and for a vent velocity of 1 m/s this would permit a peak programme sound level of 92 dB and pro rata for other vent resonance frequencies. To take a practical case, in which all the low frequency sound may be regarded as coming from the vent, such as the studio monitoring loudspeaker mentioned in Table 1, the axial response/frequency curve is -5 dB at 40 Hz with respect to the mid-band figure. This means that for a vent velocity of 1 m/s an overall peak programme sound level of 97 dB could be achieved. In fact this loudspeaker is capable of delivering a sound level of 103 dB and no complaints of bass distortion have so far been made; it appears therefore that the criterion has been too severe and that owing to the high Q of the orifice the change in total impedance caused by a small change in the resistive component is insignificant. In other words, the level of distortion generated for this value of vent velocity, is too low to be audible.

* Since the non-linearity is in the orifice, which radiates into the air, it is the velocity waveform we are concerned with not that of the pressure in the cavity which is relatively sinusoidal.

It would appear to be more practical to take the figure from Ingard and Ising just below the one which gives detectable waveform distortion, particularly as their experimental set-up represents an extreme case and will therefore err on the safe side. The figure for vent velocity is then some 5 m/s i.e. 14 dB higher than before, in which case there is some 8 dB in hand in the case of the studio monitoring loudspeaker before appreciable distortion is generated. As could be expected from the cause of the non-linearity, the distortion is symmetrical i.e. consists essentially of odd order harmonics, largely the third, provided the vent is also reasonably symmetrical.

It is possible to draw up a set of criteria for the maximum pure tone sound levels at the vent resonance frequency which should not be exceeded for vents of various sizes, and the corresponding peak programme sound levels which can be generated, assuming the response/frequency characteristic of the loudspeaker to be uniform down to these frequencies and the spectrum distribution to be that previously determined. These two sets of criteria are shown in Figs. 7 and 8. For this purpose the curve of Fig. 1 has been regarded as a straight line over the frequency range concerned. The error is less than 1 dB and in view of the data this simplification is fully justified.

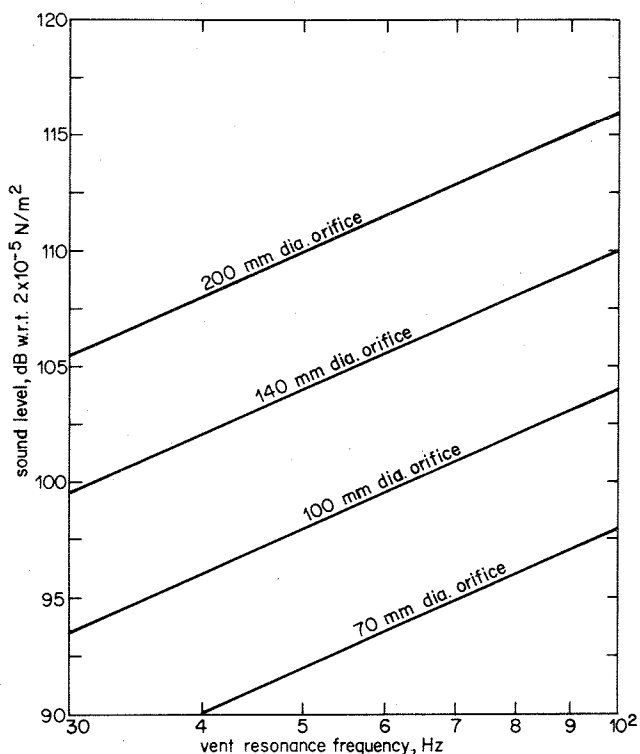


Fig. 7 - Minimum pure-tone sound levels at vent resonance frequency in room of 2000 ft³ (60 m³), for various size orifices and vent resonance frequencies, before non-linearity distortion is appreciable from orifice

The importance of the orifice area on the distortion level may be illustrated by a practical example. Fig. 9 and 10 show the level of the fundamental from a miniature loudspeaker using a vented cabinet fitted with alternative pipes of differing diameters such that the ratio of the vent

areas is about 2 to 1. To make the results more obvious the vents used were of very small diameters but their lengths were so adjusted that the vent resonance was the same in each case, about 45 Hz. (Owing to the parameters chosen the sound output at the vent resonance frequency was well below that in the mid-band.) The curves shown are the reverse of the customary ones in that they show the levels of fundamental for a constant level (-30 dB) of distortion for the third harmonic. It will be seen that, as expected, a higher sound level can be radiated, around the vent resonance frequency, for the larger vent than for the smaller one.

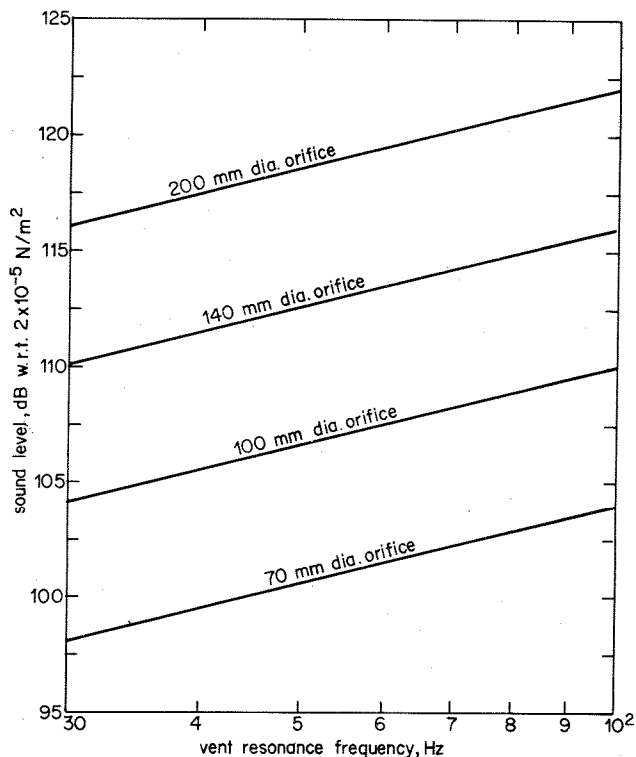
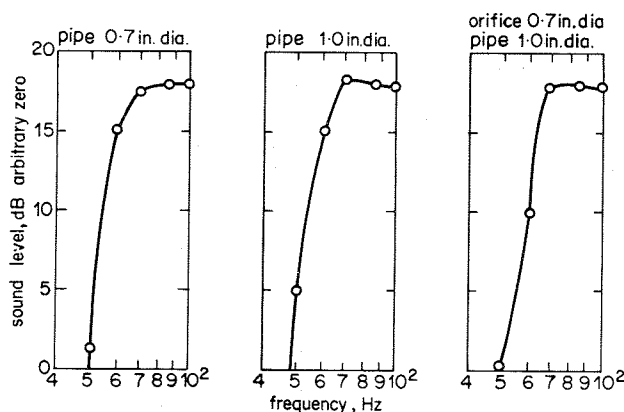


Fig. 8 - Minimum programme sound level in room of 2000 ft³ (60 m³), for various size orifices and vent resonance frequencies, before non-linearity distortion is appreciable from orifice



Figs. 9, 10, 11 - Level of fundamental tone for 3% third harmonic distortion from miniature loudspeaker fitted with various vents

Fig. 11 also shows clearly the effect of the size of the orifice itself on the distortion level. In this case the orifice was made the same size as that of the smaller vent but the larger diameter pipe was placed in series with it to give the same resonance frequency as before. It will be observed that in spite of the use of the larger diameter pipe the distortion level was determined by the size of the orifice and at approximately the same level as that of the smaller vent.

4.2.2. Distortion in a pipe

A) Non-linearity of medium at high sound pressures

As stated earlier Thuras' formula for this form of distortion is

$$p_2 = \frac{(\gamma + 1) w p_1^2 x}{20\sqrt{2}\gamma p_0 c}$$

and it is evident that unlike distortion from an orifice the distortion here is proportional to the frequency and to the length of pipe. The simplest arrangement seems to be to plot p_2 versus frequency for a 10 cm length of pipe, remembering that a typical length could be 20 cm.

As an example the sound levels permissible for a distortion level of -30 dB, i.e. 3%, may be taken, a figure which corresponds to the degree of distortion just visible on the waveform trace on an oscilloscope and therefore similar to that used in the calculation on distortion from orifices.

Rearranging the formula for distortion in a pipe we obtain

$$p_1^2 = \frac{20\sqrt{2}\gamma p_0 p_2 c}{(\gamma + 1) w x}$$

or

$$p_1 = \frac{20\sqrt{2}\gamma p_0 c}{(\gamma + 1) w x} \cdot \frac{p_2}{p_1}$$

For a value of $(p_2)/(p_1) = 0.03$, $w = 50$ Hz and $x = 10$ cm, the value of p_1 is

$$p_1 = 3.3 \times 10^5 \text{ N/m}^2$$

with a corresponding particle velocity $(p_1)/(\rho c) = 7.5 \times 10^2$ m/sec.

This will generate a sound level of 145 dB wrt 2×10^{-5} N/m² from a vent of 10 cm diameter in a room of 2000 ft³ (60 m³) and as can be seen from the formula given above the sound level for a given percentage distortion will be inversely proportional to frequency. The values for pure tones and various diameter vents are plotted in Fig. 12. As with an orifice even higher values will be permissible for the programme sound level.

In comparing these values with those of Fig. 7, it should be remembered that they are for a pipe of 10 cm

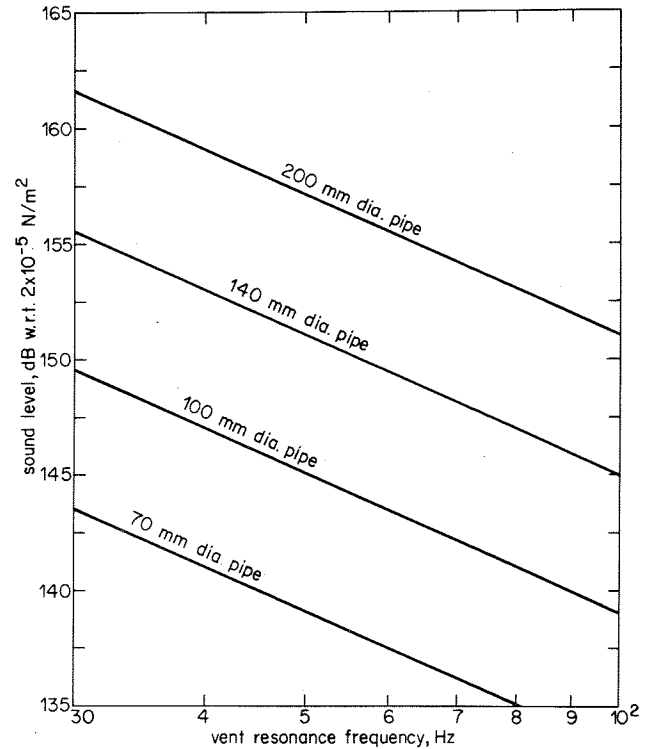


Fig. 12 - Minimum pure tone sound levels at vent resonance frequency in room of 2000 ft³ (60 m³) from vent pipes of length 100 mm and various diameters, for 3% of second harmonic distortion

length and that in practice a length of 20 cm is common which would reduce the permissible sound levels by 6 dB. It is clear, however, that even so for a given degree of distortion from this cause, much larger sound pressures may be developed by using a pipe than by a simple orifice. If, therefore, the sound pressures required are such as to lead to distortion from the latter cause then the additional use of a pipe would appear at first sight to reduce distortion because for a given inertance a larger diameter orifice will be needed if a pipe is also employed in series with it; but this is not the whole story. It is now necessary to examine the effects of high particle velocity in the pipe.

B) Distortion due to turbulence in a pipe

As stated earlier Reynolds gives the relationship for the critical velocity for laminar flow in a pipe as $(V_c d)/(\eta) = K$ where K is about 2300.

Now it is assumed in this formula that the pipe is long, which can be interpreted as meaning that the length is greater than, say, five times the diameter.

Under these conditions $V_c = 35$ cm/sec for a pipe of 10 cm diameter and pro rata for other diameters. However, just as the Q of an orifice is high and small changes in the resistive component of the impedance were found not to have a significant effect on non-linearity, so also the Q of a pipe is high and a similar state holds. Unfortunately no known measurements exist of the effect of frequency on turbulence in pipes so it will be necessary to assume the

same conditions apply as for orifices. It was shown earlier that for an orifice the lowest velocity which gave rise to detectable distortion of the waveform was approximately ten times that at which non-linearity due to turbulence commenced. A similar ratio will be used here giving a value of 3.5 m/sec for a 10 cm diameter pipe. The critical velocity is seen to be inversely proportional to diameter whilst the sound pressure in a room for constant velocity in the pipe is proportional to (diameter)², the minimum sound pressure in a listening room is therefore proportional to pipe diameter and of course proportional to frequency. This relationship is shown in Fig. 13 for pure tones. As with an orifice the programme overall sound pressures can be higher and these are shown in Fig. 14; in common with Figs. 7 and 8 the distortion is largely third harmonic.

On comparing Fig. 13 with Fig. 7 it will be seen that for large vents the use of a pipe reduces the sound pressure permissible but that as the diameter is reduced this condition changes until at diameters smaller than those shown in the figure higher sound pressures would be permissible. Unfortunately, it is in the former case that pipes are most often desirable to obtain a given inertance. In practice, the position is not quite as bad as this appears to make it, for the pipes employed with large vents are never the length postulated i.e. five times the diameter. In these circumstances the maximum sound pressures capable of being produced will lie somewhere between the two conditions. It is clear, however, that adding a pipe to a large vent can only result in a reduction of the permissible sound pressure.

Finally, it should be remembered that the turbulence both from an orifice and in a pipe has the effect of reducing the Q of the inertance. This will result, as a secondary effect, in a reduction in the output of the loudspeaker at the vent resonance frequency.

5. Conclusions

Estimates have been made of the Doppler distortion produced by recent high-quality loudspeaker designs and these figures have been compared with critical data obtained for reproducing machines. In all cases the Doppler distortion has been shown to be inaudible in the loudspeakers concerned. As far as is known, this is the first time a real assessment of actual loudspeakers has been made, and at least in these cases, has at long last shown the real degree of importance of this particular form of distortion. Design criteria have been drawn up relating the minimum sound level in a room of 2000 ft³ (60 m³) before Doppler distortion is audible on programme, the actual diameter of radiator, and the cut-off frequency.

It has also been shown that for loudspeakers in the low frequency region where the motional impedance is high, amplitudes in excess of the difference in length between the voice coil and the magnetic field do not lead to clipping of the waveform as would occur at middle and high frequencies. The amplitude of the fundamental is in excess of that which would occur if the driving force was linear and this excess can be compensated by employing a spider,

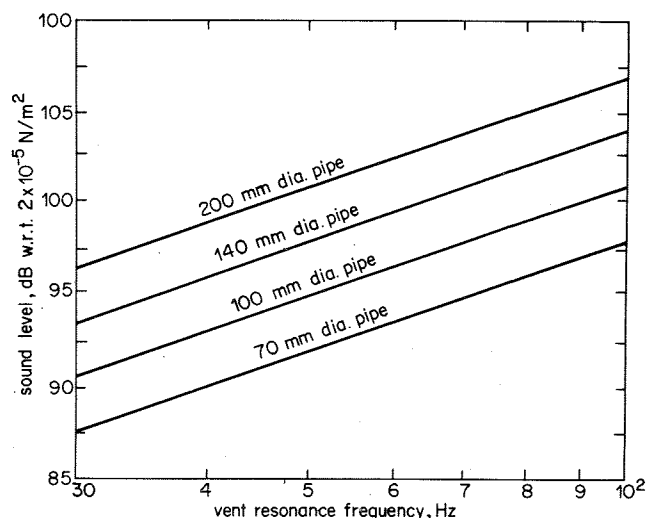


Fig. 13 - Minimum pure tone sound levels at vent resonance frequency in room of 2000 ft³ (60 m³), for various diameter long pipes and vent resonance frequencies, before distortion is appreciable

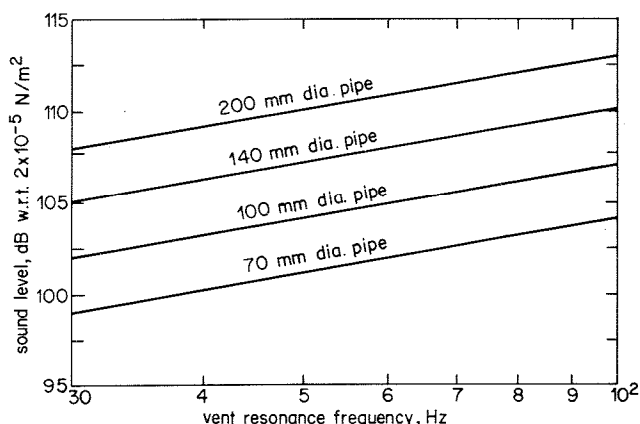


Fig. 14 - Minimum programme sound levels in room of 2000 ft³ (60 m³), for various diameter long pipes and vent resonances, before distortion is appreciable

surround and cabinet, having the corresponding non-linear stiffness. Under these conditions an appreciable increase in loudspeaker output is possible, for a given level of distortion, without any reduction in sensitivity.

Finally, non-linearity distortion from vents in loudspeakers has been shown to be caused by turbulence at the orifice, by turbulence in the pipe and by high sound pressures in the pipe. Employing such data as is available calculations have been made of the minimum sound levels to be expected in a listening room of 2000 ft³ (60 m³) before distortion from these sources is audible and that from the high sound pressure in the pipe has been shown in practice not to be a limiting factor. For small vents distortion from the orifice predominates whilst for large vents pipes are to be avoided as far as possible. Design data for these conditions has been drawn up.

It will be appreciated that distortion from the first mentioned cause, Doppler effect, extends over a wide range

of frequencies but that from the second two is confined to the bass.

It is also evident that by proper design the first and last types of distortion need not be limiting factors at the sound levels used in listening rooms.

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APPENDIX:
Amplitude distortion in loudspeakers due to non-linearity of the magnetic field

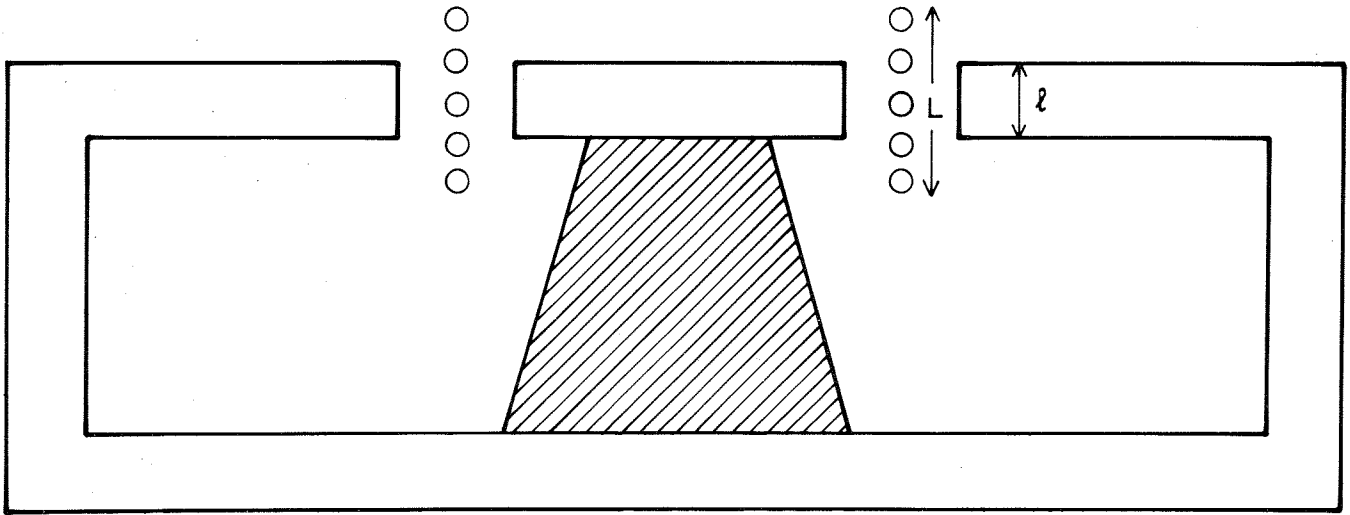


Fig. 1A - General arrangement of the voice coil in relation to the magnetic field

At resonance it will be assumed that the cone velocity is given by

$$\frac{dx}{dt} = \frac{B \lambda i}{Z} \quad (\text{A1})$$

where

x is the displacement of the coil at time t

B is the average flux at time t

i is the current in the conductor

λ is the length of the conductor

Z is the mechanical resistance of the system

since at resonance cone velocity is in phase with and proportional to the driving force $B\lambda i$, and the ratio of the driving force to the cone velocity is by definition the mechanical resistance.

For a constant voltage input E , the current i is given by

$$i = E / \left(r + \frac{(B\lambda)}{Z} \right) \quad (\text{A2})$$

where r is the electrical resistance of the voice coil. (This can be neglected, except insofar as it ensures the (A10.1) below always yields a real positive value of $(L + 1 - x)$. It will be assumed that Equation (A2) also applies if

$$E = E_0 \cos wt \quad (\text{A3})$$

when w is sufficiently small.

The relation between B , the average flux at any instant, and x , the coil displacement, is

$$\left. \begin{aligned} B &= B_0 (0 < x < L - 1) \\ B &= B_0 (L + 1 - x) / (21) \quad L - 1 < x < L + 1 \end{aligned} \right\} \quad (\text{A4})$$

and it will be shown that x can approach $(L + 1)$ from below but cannot exceed $L + 1$.

Suppose that when $t = 0$, $x = 0$ and that the applied voltage is thereafter given by Equation (A3). Then initially $B = B_0$, and from Equations (A1) and (A2)

$$dx/dt = wp_0 \cos wt \quad (\text{A5})$$

where the 'pseudo-amplitude' p_0 is defined by

$$p_0 = B_0 E_0 \lambda / [w(rZ + B_0^2 \lambda^2)] \approx \frac{E_0}{B_0 \lambda w} \quad (\text{A6})$$

$$\text{If} \quad p_0 \leq L - 1 \quad (\text{A7})$$

then Equation (A5) applies indefinitely; the régime is wholly linear and

$$x = p_0 \sin wt \quad (\text{A8})$$

so that p_0 is the actual amplitude of the displacement. When Equation (A7) is not satisfied, however, there is a time t_1 , ($0 \leq t_1 \leq \pi/2w$) such that

$$\sin wt_1 = (L - 1)/p_0 \quad (\text{A9})$$

so that Equation (A8) only applies for $0 \leq t \leq t_1$, and it is necessary now to formulate equations governing the motion for $t_1 \leq t \leq \pi/2w$, when B is no longer constant but depends on x .

From Equations (A1), (A2), (A3), (A4) and (A9), the formula for the displacement x at time $t > t_1$, can be reduced to

$$\frac{(L+1-x)^2}{4l} - \frac{2lZ}{\lambda^2 B_0^2} \log_e \frac{2l}{L+1-x} = L - p_0 \sin wt \quad (\text{A10.1})$$

Neglecting r this reduces to

$$x = (L+1) - \left\{ 4lL - 4lp_0 \sin wt \right\}^{1/2} \quad (\text{A10.2})$$

In all detailed numerical work, r , the electrical resistance of the voice coil will be neglected. The significance of this term is that if $p_0 > L$, so that there is a value of t for which the right hand side of (A10) is zero in the range $t < t < \pi/(2w)$, then there is a value of x near and below $(L+1)$ which makes the left hand side of (A10.1) zero. For when x tends to $L+1$, the first term of (A10.1) tends to zero and the second on the left hand side tends to $-\infty$, whereas if x is less than $L+1$, the first term of (A10.1) is positive and the second term on the left hand side is small, since it is proportional to r .

The general method of attack will be to use Simpson's Rule for numerical integration of $x \sin wt$ and $x \sin 3wt$ over the range 0 to $\pi/(2w)$ to obtain the fundamental and third harmonic terms. Strictly speaking, Simpson's Rule is not applicable when $\sin wt \approx L/p_0$ because if r is neglected, x then has a singularity. It will be assumed here that Simpson's Rule is applicable for $(L-1) \leq \sin wt \leq (L/p_0) - E$, and that $x = L+1$ for $\sin wt \geq (L/p_0) - E$ where the precise value of E is not critically important. If

$$\sin wt_2 = L/p_0 \quad (\text{A11})$$

E will be chosen so that the change-over from the Simpson's Rule regime so that in which $x = L+1$ is deemed to occur when wt is about 0.2° less than wt_2 , and is con-

veniently rounded when expressed in degrees. This is a somewhat rough and ready, arbitrary procedure, but the errors involved are small enough for such procedure to be adequate; such errors are included within that involved in neglecting r , which is clearly an advantageous simplification.

Equation (A10.2) will be used to evaluate the fundamental and third-harmonic components of the displacement x for $p_0/(L-1) = 0.5, 1, 1.5, 2, 4, 6, 8, 10, 15$ and $p_0 \rightarrow \infty$ (A12) and taking $L = 0.25$ inches (0.533 cm).

For $0 \leq t \leq t_1$, (neglecting r)

$$x = p_0 \sin wt \quad (\text{A12})$$

whatever p_0 may be. By symmetry, only odd-harmonic sine-terms are involved and the contributions of the linear régime to the fundamental and third harmonic are respectively

$$\begin{aligned} \text{Fundamental: } & \frac{p_0}{\pi} \left[2wt_1 - \sin 2wt_2 \right]; \\ \text{3rd harmonic } & \frac{p_0}{\pi} \left[\sin 2wt_1 - \frac{1}{2} \sin 4wt_1 \right] \end{aligned} \quad (\text{A13})$$

and the corresponding contributions from the régime in which $x = (L+1)$ are

$$\begin{aligned} \text{Fundamental: } & \frac{4}{\pi} (L+1) \cos (wt_2 - \eta); \\ \text{3rd harmonic, } & \frac{4(L+1)}{3\pi} \cos 3(wt_2 - \eta) \end{aligned} \quad (\text{A14})$$

where η is the arbitrary correction of wt_2 — a reduction of about 0.2° — already discussed.

Results are given in Table 2 below.

TABLE 2
Fundamental and Third-Harmonic Components for Various p_0
 $L = 0.25$ in. $l = 0.21$ in.

p_0	$p_0/(L-1)$	wt_1 (degrees)	Fundamental	3rd Harmonic	% Third	Remarks
0.02	0.5	—	0.02	0	0	Régime
0.04	1	90.00°	0.04	0	0	wholly linear
0.06	1.5	41.81°	0.06028	-0.00017	-0.28	
0.08	2	30.00°	0.08133	-0.00069	-0.85	
0.16	4	14.478°	0.17808	-0.00674	-3.78	
0.24	6	9.594°	0.32239	-0.03548	-11.01	Max. negative 3rd harmonic is when $p_0 = L$
0.32	8	7.181°	0.47499	-0.02514	-5.29	3rd harmonic decreasing because x cannot exceed $L+1$
0.40	10	5.739°	0.51953	+0.03773	+7.27	
0.60	15	3.823°	0.55783	0.11909	+21.35	
0.80	20	2.866°				These cases do not appear to be worth doing
1.20	30	1.91°				
∞	∞	0°	0.58569	0.19523	33.33	Régime is effectively a square wave

The outstanding feature of the results in Table 1 is that there should be almost complete freedom from third-harmonic distortion when $p_o/(L - 1)$ is in the neighbourhood of 9 for the particular case considered.

The procedure used in this Appendix could easily be extended to cover higher-harmonic (5th, 7th, etc) distortion, but as all the even harmonics are zero by symmetry, the third harmonic seems to be much the most important.